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ORIGINAL PAPER

A fast GIS-based risk assessment for tephra fallout: the example of Cotopaxi volcano, Ecuador-Part II: vulnerability and risk assessment

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Abstract In order to develop efficient strategies for risk mitigation and emergency management, planners require the assessment of both the expected hazard (frequency and magnitude) and the vulnerability of exposed elements. This paper presents a GIS-based methodology to produce qualitative to semi-qualitative thematic risk assessments for tephra fallout around explosive volcanoes, designed to operate with datasets of variable precision and resolution depending on data availability. Due to the constant increase in population density around volcanoes and to the wide dispersal of tephra from volcanic plumes, a large range of threats, such as roof collapses, damage to crops, blockage of vital lifelines and health problems, concern even remote communities. To address these issues, we have assessed the vulnerability and the risk levels for five themes relevant to tephra fallout: (1) social, (2) economic, (3) environmental, (4) physical and (5) territorial. Risk and vulnerability indices for each theme are averaged to the fourth level of administrative unit (*parroquia*, parish). In a companion paper, Biass and Bonadonna (this volume) present a probabilistic hazard assessment for tephra fallout at Cotopaxi volcano (Ecuador) using the advection-diffusion model TEPHRA2, which is based on field investigations and a global eruption database (Global Volcanism Program, GVP). The scope of this paper is to present a new approach to risk assessment specifically designed for tephra fallout, based on a comprehensive hazard assessment of Cotopaxi volcano. Our results show that an eruption of moderate magnitude (i.e. VEI 4) would result in the possible collapse of $\sim$9,000 houses in the two parishes located close to the volcano. Our study also reveals a high risk on agriculture, closely linked to the economic sector, and a possible accessibility problem in case of an eruption of any size, as tephra is likely to affect the only major road running from Quito to Latacunga (Panamerican Highway). As a result, this method fits into the ongoing effort to better characterize and evaluate volcanic risk, and more specifically the risk associated with tephra fallout. Although this methodology relies on some assumptions,

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it can serve as a rapid and efficient starting point for further investigations of the risk level around explosive volcanoes.

Keywords Volcanic hazard · Volcanic risk · Vulnerability · Tephra dispersion · GIS · Cotopaxi · Ecuador

1 Introduction

This study combines probabilistic modelling of tephra dispersal with a thematic vulnerability assessment using free and global data in order to achieve a qualitative to semi-qualitative risk assessment for tephra fallout. In a companion paper (Biass and Bonadonna, this volume), we have detailed each step of the process of compiling probabilistic hazard maps, including (1) the identification of the most likely eruptive scenarios, (2) the assessment of the probability of recurrence of eruptions of classes defined by the volcanic explosivity index (Newhall and Self 1982, VEI), (3) the statistical analysis of wind patterns over the region of interest and (4) the production of several outputs (i.e. probability maps, isomass maps, hazard curves) designed to help planners and decision-makers. The present paper focuses on two aspects. First, a vulnerability assessment for tephra fallout based on free and easily accessible data was achieved, for which several vulnerability themes have been developed along with specific indicators for each theme. Second, a risk assessment was compiled in which new ways of combining probabilistic hazard assessments and thematic vulnerability assessments have been explored, including an attempt to define common hazardous thresholds of tephra accumulation for all vulnerability themes considered. As a result, this study proposes new strategies for the risk assessment related to tephra fallout able to combine geological and geographical datasets of varying precision and scales. Where the method is not able to quantify the expected losses, it still provides qualitative indications of the potential impact of tephra fallout. As an example, this strategy was applied to the area located around Cotopaxi volcano, Ecuador (Fig. 1).

1.1 Summary of the hazard assessment

The hazard assessment for tephra fallout was performed using the advection-diffusion model TEPHRA2 (Bonadonna et al. 2005) and probabilistic methods developed by Bonadonna (2006). The evaluation of the past eruptive behaviour was based on both field data (Barberi et al. 1995; Biass and Bonadonna 2011) and a thorough study of the Global Volcanism Program of the Smithsonian institution (Siebert and Simkin 2002, GVP), based on which we have decided to focus on eruptions of VEI of 3–5 (bulk volumes between 0.01 and 10 km^3; Newhall and Self 1982). The probability of an eruption of a given magnitude occurring within a hypothetical time period (i.e. 10 and 100 years) was calculated for each VEI class, based on a Poisson process (De la Cruz-Reyna 1993; Borradaile, 2003; Mendoza-Rosas and la Cruz-Reyna 2008; Dzierma and Wehrmann, 2010). Probabilities of an eruption in the next 100 years are 0.781, 0.202 and 0.006 for VEIs 3, 4 and 5, respectively (Biass and Bonadonna, this volume).

A statistical analysis of wind patterns was achieved using the NOAA NCEP/NCAR Reanalysis 1 dataset (Kalnay et al. 1996). After an assessment of the variability of Monte Carlo simulations, it was decided to use a dataset of 12 years of wind (1997–2008) providing 4 daily measurements.

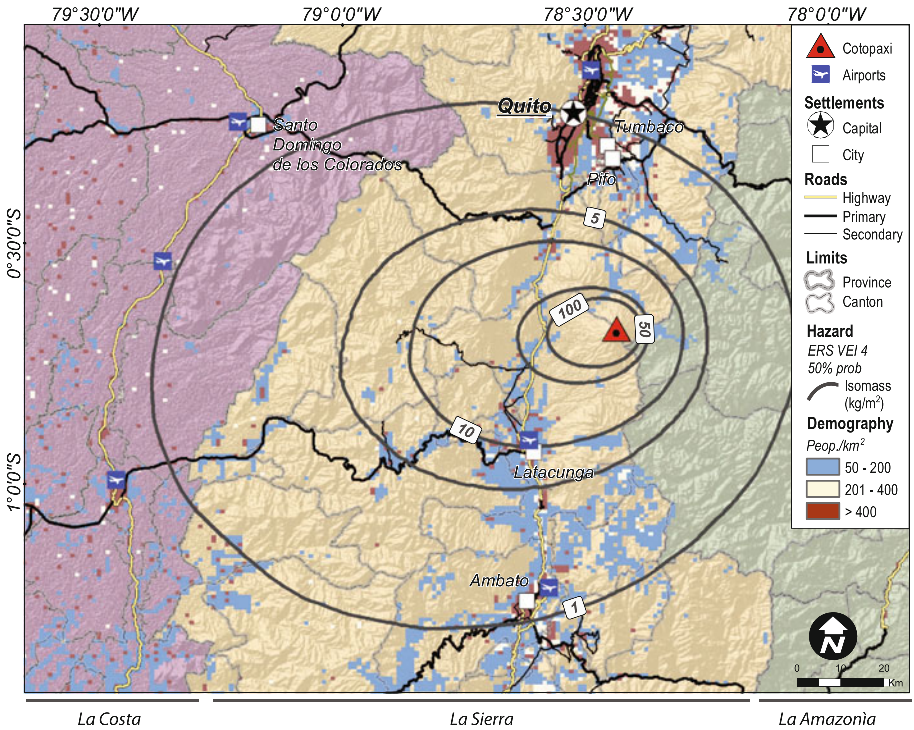

Fig. 1 Overview map around Cotopaxi volcano, showing exposed elements (human settlements, roads, airports), the hazard scenario used throughout this study (isomass map for an ERS of VEI 4–50 % probability of occurrence; Biass and Bonadonna, this volume) and the topographic context. The population density is inferred from the LandScan 2005 dataset. This area of Ecuador is divided into three regions: (i) *La Sierra* (*central*, *orange*), (ii) *La Costa* (*west*, *purple*) and (iii) *La Amazonia* (*east*, *green*)

The modelling framework consists of two probabilistic approaches described in Bonadonna (2006). First, the *One Eruption Scenario* (OES) compiles the probability of reaching a given ground tephra accumulation with a varying wind and eruptive parameters deterministically defined. Two large eruptions have been considered, namely Layer 3 and Layer 5 (of VEIs 5 and 4, respectively; Barberi et al. 1995; of VEIs 5 and 4, respectively; Biass and Bonadonna 2011). Second, the *Eruption Range Scenario* (ERS) assesses the probability of reaching a given tephra accumulation based on the statistical distribution of both wind profiles and eruptive parameters. In particular, eruptive parameters were stochastically sampled within mass and plume heights defined for each VEI 3, 4 and 5 classes (Newhall and Self 1982). Using the resulting data from ERS modelling, a long-term ERS assessment for different time lengths was produced by summing the products of each separate VEI with their respective probabilities of occurrence. Each scenario was run 1,000 times.

Finally, the hazard assessment was produced in the form of three complementary outputs. First, probability maps contour the probability of reaching a given hazardous threshold of tephra accumulation and are important to evaluate the variation of probability for a specific hazardous threshold (e.g. damage to crops, roof collapse). Second, probability maps were transformed into isomass maps for a given probability, from which we can infer the acceptable risk when combined with vulnerability data. This approach was chosen when combining hazard data with vulnerability data, as it provides a geographical variability of the hazardous phenomenon for a fixed probability of occurrence. Third, hazard curves are an efficient way of displaying the exceeding probability of tephra accumulation for a key location and allow different eruptive scenarios to be effortlessly compared. For further details, the reader is referred to Biass and Bonadonna (this volume).

This method was developed using the software *ESRI ArcMap* 9.3©, but the simple nature of most of the arithmetic operators used during the analysis makes this methodology usable with most GIS platforms without major discrepancy. In order to present the method in a concise way, this paper illustrates two vulnerability themes (i.e. economic and physical) with one medium intensity eruptive scenario. The eruptive scenario chosen as an example is an ERS for VEI 4, with plume heights and erupted masses varying between 15 and 30 km and $1 - 10 \times 10^{11}$ kg, respectively (Fig. 1). Hazard maps for all eruption scenarios can be found in Online Resource 1 of Biass and Bonadonna (this volume). Vulnerability and risk maps for all eruption scenarios and vulnerability themes are available in Online Resource 1 and 2 of this paper.

2 Vulnerability assessment

The concept of vulnerability is the cornerstone of the process of evaluating the risk of an element exposed to a hazardous event, which differentiates an isolated physical phenomenon from a natural disaster (O'Keefe et al. 1976). Early definitions of vulnerability focused mainly on the intrinsic susceptibility of structures to be damaged by natural phenomena (UNDRO 1991) and lacked to address the effect felt by individuals and communities (Dibben and Chester 1999). More recent definitions describe vulnerability as "a combination of factors that determine the extent to which a person's life, livelihood or general well-being is threatened by an extreme event of nature" (Blaikie et al. 1994)," or as "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of a community to the impact of hazards" (UN/ISDR 2004). Vulnerability is a dynamic process, which varies geographically, over time, and amongst different social groups (Cutter et al. 2003).

Three observations should be made regarding the use of vulnerability in this study. First, rather than considering vulnerability as an intrinsic property of a system or element (UN/ISDR 2004), this paper considers it as being conditional on a specific hazard, that is, tephra fallout (UNDRO 1991). It has been argued by Blaikie et al. (1994) that vulnerability analysis is of limited values in areas of volcanic hazards due to the high destructive power of volcanic phenomena (e.g. pyroclastic flows, lahars). This statement ignores hazards related to the fallout of tephra, which are likely to disrupt a wide range of aspects of human activities and economic sectors even far from the erupting vent, though responsible for only 2 % of recorded volcano fatalities (Simkin et al. 2001). Second, vulnerability assessments should be regarded as a two-level process: a first qualitative analysis emphasizes the fragility (i.e. economy, environment, accessibility) of a community facing a threatening event, and a second more detailed quantitative analysis that can assess the potential direct impacts of a phenomenon on a community and its environment (Stieltjes and Mirgon 1998; Aceves-Quesada et al. 2007). This work presents a qualitative vulnerability assessment for a given study area, aimed at providing tools for developing an appropriate response (emergency planning) and risk mitigation measures through land use planning.

Third, while early works tended to focus on vulnerability of populations, it has been admitted that these populations have intrinsic ways to cope and overcome natural disasters, giving rise to factors able to increase or decrease the state of vulnerability (Cardona 2003). As a result, recent works have widened the concept of vulnerability to incorporate resilience or coping capacity as one of the dominant components of the analysis (Wisner et al. 2004; Birkmann 2007; Frischknecht et al. 2010). Large-scale studies, as the one presented here, are based on global data and are therefore not able to capture cultural aspects. As an example, census surveys such as the one used here are not specifically designed for risk analysis and thus neglect important information about hazard perception and mitigation parameters (Ebert et al. 2009). The analysis presented here only focuses on factors increasing vulnerability, leaving the assessment of factors decreasing vulnerability (i.e. resilience) for a separate study. Nonetheless, this method aims at providing a solid basis for a more detailed analysis incorporating precise in situ social surveys.

2.1 Material

Vulnerability and risk assessments are complex tasks, involving a wide variety of processes that require large amounts of spacial (i.e. land use, road network, settlements, elevation) and temporal (wind patterns, variation of population density) data coming from disparate sources (El Morjani et al. 2007). However, the main limitations in the application of geo-informatics remain the following: (1) the high data demand and cost, (2) the need for an integrated analysis of multi-type/format data, (3) the need of frequent updates of such data and (4) datasets of parameters that are difficult to map directly, such as those relevant to the assessment of social vulnerability (Ebert et al. 2009). The concern of this study is to propose a method that combines global, easily accessible and free datasets, but which could be equally applied to more detailed and precise datasets if available.

The vulnerability and risk assessments were achieved using GIS tools and their abilities to input, manage, manipulate, analyse and process georeferenced data (Aronoff 1989). The first step of the creation of a GIS database is to collect relevant thematic data, which can be problematic depending on the study area and budget restrictions. This section describes free and global datasets used in this study.

2.1.1 Social census

The main source of socio-economical data has been the *2001 Censo de poblacion y vivienda* from the *Instituto Nacional de Estadisticas y Cencos de Ecuador* (INEC 2001), from which vulnerability indicators explained in Sect. 5 have been defined. Additionally, it provided a precise census of building types as well as shapefiles for administrative units. The INEC dataset has been converted to a GIS database using *Matlab* © routines.

2.1.2 Roads and place names

Roads and place names have been inferred from the OpenStreetMap database (OpenStreetMap 2010). Although complete datasets are only available for few places around the world, we believe it will soon become a valuable tool for risk assessment thanks to the increasing number of contributions from users. Moreover, the OpenStreetMap project is aiming at mapping not only roads, but also a whole range of features such as hospitals, schools, airports, administrative boundaries or natural parks.

2.1.3 Protected areas and intact forests

Shapefiles on protected areas are freely available from the website of World Database on Protected Areas (WDPA 2011). On the basis of a compilation of data from multiple actors, this database provides up-to-date datasets on worldwide marine and terrestrial protected areas. In a similar way, the Intact Forest Landscape database from Greenpeace (Potapov et al. 2008) maps the unbroken expanse of natural ecosystems within the zone of current forest extent, showing no signs of significant human activity.

2.1.4 Land cover

Land use was inferred using the ESA Ionia GlobCover dataset (ESA 2006). This dataset was produced between 2004 and 2006 using ENVISAT's Medium Resolution Imaging Spectrometer (MERIS) Level 1B, with a resolution of 300 m. It is based on the UN Land Cover Classification System (LCCS).

2.2 Delineation of proxy variables for vulnerability assessment

Vulnerability assessments are typically achieved by (1) defining vulnerability "themes", (2) defining vulnerability indicators for each theme and (3) weighting each parameter to compile final global vulnerability maps (D'Ercole 1996; Stieltjes and Mirgon 1998; Torrieri 2002; Aceves-Quesada et al. 2007; El Morjani et al. 2007). Since the main limitation of this study was the availability and the precision of the wide variety of data required by our analysis, we had to define vulnerability indicators based on the free and global datasets described above.

We considered five themes for the region around Cotopaxi volcano: (1) social vulnerability, (2) economic vulnerability, (3) environmental vulnerability, (4) physical vulnerability and (5) territorial vulnerability, which are described in detail in the next section. Each vulnerability theme was averaged to the fourth level of administrative unit, namely *parroquias* or parrish, and classified in 5 classes (*very low, low, medium, high and very high*) using Jenks Optimization methods implemented in most GIS softwares (Table 1).

In most vulnerability assessments (Aceves-Quesada et al. 2007; Stieltjes and Mirgon 1998; D'Ercole 1996), experts are required to weigh each vulnerability indicator within each theme, and to then weigh each theme to produce global vulnerability maps. We have chosen to give the same weight to all indicators and to produce thematic vulnerability maps instead of global vulnerability maps for several reasons. First, the georeferenced datasets we were able to gather for each theme come from a wide range of sources. Therefore, a lack of consistency amongst datasets was often found, making comparison difficult. Second, weighting of vulnerability indicators is typically achieved using Multi-Criteria Evaluation (Saaty 1980, 2008; Malczewski 2006; Aceves-Quesada et al. 2007), which is based on an extended knowledge of the concerned geographical area. Remote studies like ours do not allow such assessments related to precise socio-economic contexts, and we chose not to rank vulnerability parameters. Modern GIS tools make Multi-Criteria Evaluations relatively easy and rapid, and such process could therefore be easily added to the resulting thematic vulnerability maps obtained with our method. Finally, since the aim of the present paper is to develop a method to assess the vulnerability (and the risk) related to tephra fallout, thematic vulnerability maps might be more efficient than global vulnerability maps to reveal the strengths and weaknesses of different administrative units towards this hazard.

Table 1 Indicators for each vulnerability theme and thresholds used to identify vulnerability classes

Theme	Indicator	Vulnerability level				
		Very low 1	Low 2	Medium 3	High 4	Very high 5
Social	Total population	0–3,033 inh.	3,034–9,564 inh.	9,565–27,533 inh.	27,534–47,390 inh.	47,391–503,722 inh.
	Education level	44–65 %	65.1–71 %	71.1–76 %	76.1–80 %	80.1–88 %
	C/S/I*	36–43 %	43.1–47 %	47.1–52 %	52.1–57 %	57.1–68 %
Economic	% of agricultural lands	0–12 %	12.1–28 %	28.1–47 %	47.1–67 %	67.1–99 %
Environmental	% of protected forests	0–5 %	5.1–16 %	16.1–39 %	39.1–59 %	59.1–83 %
	% of natural areas	0–4 %	4.1–16 %	16.1–36 %	36.1–60 %	60.1–99 %
Physical	% of weak buildings	0–20 %	20.1–40 %	40.1–60 %	60.1–80 %	80.1–100 %
Territorial	Nb of hospitals	0–1	2–3	4–7	8–10	11–58
	Nb of military bases	0–1	2–3	4–8	9–30	31–59
	Cost distance to closest airport	1.4×10^6–2.1×10^7	2.2×10^7–4.3×10^7	4.4×10^7–7.5×10^7	7.6×10^7–1.5×10^8	1.6×10^8–2.7×10^8

* Proportion of children, seniors and invalids. *Nb* number, *Inh* inhabitants

Classes for each vulnerability theme were defined using Jenks Optimization methods (Jenks 1967). Weak buildings were defined as being impacted by a tephra accumulation of 100 kg/m^2. See Online Resource 3 for a detailed list of vulnerability indicators for all administrative units, and Online Resource 4 for their respective hazard indices

2.2.1 Social vulnerability

Rapid progresses on the topic of physical vulnerability (vulnerability of the built environment) have often shadowed the assessment of social vulnerability (Cutter et al. 2003). Physical vulnerability being the topic of engineers, social aspects of vulnerability were largely ignored for a long time, mainly due to the difficulty of quantifying the complex web of indicators required for such analysis (Cutter et al. 2003). Wisner et al. (2004) define social vulnerability as “the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard”. As argued above, recent studies tend to separate the concepts of coping capacity and vulnerability (Frischknecht et al. 2010); as a result, we have chosen to focus on elements that increase vulnerability.

The simplified assessment of social vulnerability presented here is based on three indicators (for each administrative unit): (1) total population, (2) education level and (3) proportion of more vulnerable people, namely children, seniors and invalids, inferred from the 2001 *Censo de poblacion y vivienda from the Instituto Nacional de Estadisticas y Cencos de Ecuador* (INEC 2001). These factors were adopted based on Wisner et al. (2004), Cutter et al. (2003) and Aceves-Quesada et al. (2007). The *education level* indicator was defined as the ratio of people without a basic level of education on the total population of the administrative unit. In the absence of any precise age threshold for children, we have followed the most commonly used age threshold of 15 years old, which conveniently fits with the INEC database. Following definitions from the World Health Organisation (WHO 2011), the age limit for seniors was set at 65. A detailed list of vulnerability indicators for all administrative unit can be found in Online Resource 3.

Table 1 shows classification levels for each vulnerability indicator, defined from *Jenks Optimization Methods* (Jenks 1967) on the whole datasets of administrative units. The resulting social vulnerability map can be found in Online Resource 1, showing that *La Costa* region is the most vulnerable due to a lower education level, followed by *La Sierra* and *La Amazonìa* regions. Administrative units comprising main cities are usually a combination of high population levels versus high education levels, resulting in most cases in low to medium vulnerabilities.

2.2.2 Economic vulnerability

Initial studies of vulnerability tended to combine together economic and environmental vulnerabilities, although it rapidly became obvious that these two aspects were to be analysed separately (Guillaumont 2000). This study illustrates how the same element (i.e. natural environment, but here more specifically vegetation) can be described in both economic vulnerability and environmental vulnerability indicators with different implications.

In the context of natural disasters, Guillaumont (2000) defines the concept of economic vulnerability as the relative susceptibility to damage caused by natural disasters. In this study, due to the absence of economic data, we have assumed that the main source of income for most of the study area was related to agriculture. As a result, the economic vulnerability indicator used here is given by the ratio between the areas of crop land over the total area of each administrative unit. Since agriculture is the main source of income in rural regions around Cotopaxi volcano and little amounts of tephra fallout can already disrupt its production (Blong 1984), our qualitative vulnerability assessment is able to provide insights into the most vulnerable administrative units, as a first step towards a better land use management. Nonetheless, a more detailed analysis of all economic sectors should be carried out for a comprehensive vulnerability assessment.

Reviews of impacts of tephra fallout on vegetation can be found in Blong (1984); Inbar et al. (1995); Wisner et al. (2004); Martin et al. (2009); and Wilson et al. (2011a, b). Following the study of Blong (1984) on the impacted vegetation after the 1943–1952 eruption of Paricutin volcano (Mexico), four zones depending on the tephra thickness were defined: 2nd zone of partial survival (150–500 mm), 1st zone of partial survival (500–1,500 mm), nearly total kill zone ($\sim$1,500 mm) and total kill zone ($\geq$1,500 mm). The assessment of the economic vulnerability presented here does not consider values of tephra accumulation reaching a "kill" zone, as a disruption of one season of harvest already bears economic consequences. Although the sensitivity to tephra fallout of individual species strongly varies and goes beyond a linear relationship between tephra thickness and impact (Wilson et al. (2011a), we have generalized the impact on harvests to accumulations ranging from 10 to 150 mm (Blong 1984).

Table 1 shows how classes for economic vulnerability were defined. Figure 2a and Online Resource 2 show the resulting economic vulnerability maps, displaying a high vulnerability for the region of *La Costa*. The second most vulnerable area is the bottom of the Interandean valley, due to a more suitable land for agriculture than in the surrounding steep valley flanks.

2.2.3 Environmental vulnerability

The natural environment is vulnerable to natural hazards. Williams and Kapustka (2000) define the concept of environmental vulnerability as an estimate of the inability of an ecosystem to tolerate stressors over time and space. Such a general definition makes it difficult to decompose the concept of vulnerability into a set of indicators (Villa and McLeod 2002), especially in the context of volcanic eruptions, which have the power of disrupting the environment at all scales. Proximal areas are under the direct influence of pyroclastic flows, lahars, lava flows and volcanic bombs, all characterized by a very high destructive power (Annen and Wagner 2003); distal areas (>10s km) are dominated by tephra fallouts and their ability to impact vegetation and contaminate water (Inbar et al. 1995; Martin et al. 2009; Wilson et al. 2011a, b, c); localized ozone holes can occur at continental scale due to halogen emissions (Millard et al. 2006), and the truly global scale can also be impacted with climatic effects of sulphuric acid aerosols (Robock, 2000). The present environmental vulnerability analysis focuses on the susceptibility of the vegetation to be affected by tephra accumulations reaching the near total kill zone, as described in the previous section (Blong 1984).

As a result, we have described here the environmental vulnerability of administrative units using two indicators, mainly focusing on aspects of vegetation: (1) the area covered by intact forests (Potapov et al. 2008) and (2) the area covered by protected areas (WDPA 2011). Both values were normalized on the total area of each administrative unit. Although these indicators cover only a small part of the general definition of Williams and Kapustka (2000), they provide key insights into fundamental environmental aspects of Amazonian countries. Due to the extent of the Amazonian forest, *La Amazonìa* region as well as the easternmost part of *La Sierra* region display the highest degrees of vulnerability. Protected areas are mainly concentrated in the flanks of the Interandean valley in *La Sierra*, making this region the second most vulnerable. The environmental vulnerability map can be found in Online Resource 2.

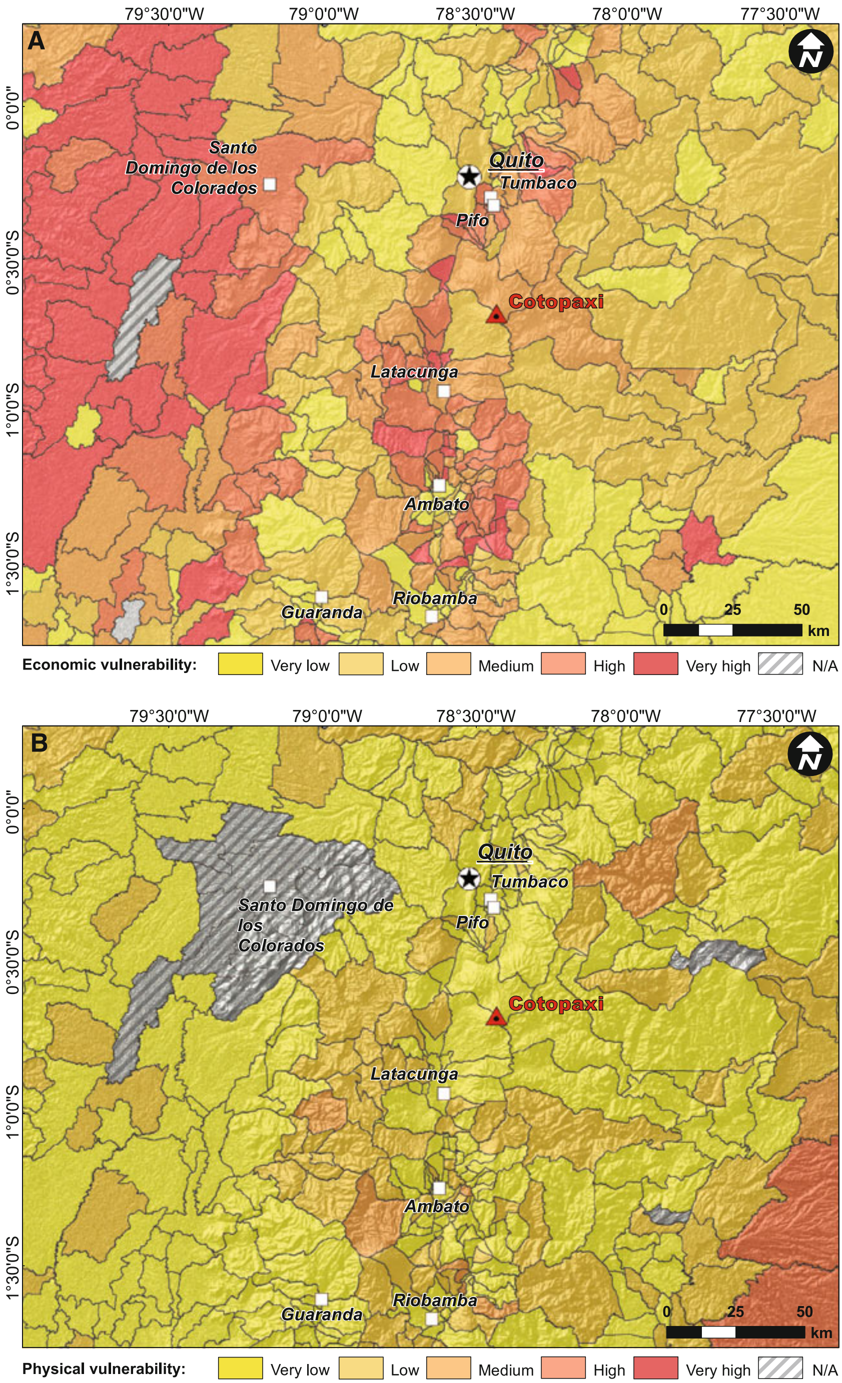

Fig. 2 Thematic vulnerability maps per *parroquia* for **a** economic vulnerability and **b** physical vulnerability. *N/A* refers to gaps in the census survey. Vulnerability classes are defined using values in Table 1. Vulnerability maps for all themes can be found in Online Resource 1

2.2.4 Physical vulnerability

Physical vulnerability describes the susceptibility of infrastructures to be damaged by natural hazards (Ebert et al. 2009). In the context of tephra fallout, the most observed impact is the collapse of roofs under tephra load. Even though this threat is responsible for only 2 % of recorded volcano fatalities since AD 1, it has been cited as a cause of death in 21 % of volcanic eruptions, making it the most frequently occurring cause of death (Simkin et al. 2001; Spence et al. 2005).

It has been pointed that the vulnerability of roofs to tephra fallout depends on the type, the height, the age, the load-bearing structures, the type of roof, the dimension and the general layout of the building (Blong 1984, 2003; Pomonis et al. 1999; Spence et al. 2005), making this type of assessments geographically dependent and requiring extensive in situ surveys. Vulnerability curves have been developed after the 1991 eruption of Pinatubo (Spence et al. 1996) and the 1994 eruption of Rabaul (Blong 2003), which can be in some cases extended to other situations. In Europe, the most complete surveys were performed on the island of Sao Miguel, Azores (Pomonis et al. 1999), for the areas around Vesuvius (Zuccaro et al. 2008), around Mt. Etna (Barsotti et al. 2010) and for Icod de los Vinos, Tenerife (Marti et al. 2008). The range of impact of tephra load on roofs found in the literature usually shows minor damage from 100 kg/m^2 to major damage at 700 kg/m^2 (Blong 1984; Bonadonna 2006). However, in the case of Ecuador and based on data in Metzger et al. (1999) and Hugo Yepes (personal communication), we have adopted a range from 100 to 300 kg/m^2 with a vulnerability linearly increasing from 0 to 1 between those values (Table 1).

Our physical vulnerability assessment is based on the 2001 *Censo de poblacion y vivienda* from the *Instituto Nacional de Estadı̀sticas y Cencos de Ecuado* (INEC 2001), which provides a building census for each administrative unit divided into 7 building types, ranging in increasing quality: *choza, covacha, rancho, mediagua, cuarto, casa o villa* and *departamento*. After a survey of pictures available on Google Earth, we classified these types of buildings into 3 classes, from high to low vulnerability: (1) *choza, covacha* and *rancho* as being potentially damaged from a tephra accumulation of 100 kg/m^2; (2) *mediagua*, potentially damaged from 200 kg/m^2 and (3) *cuarto, casa o villa* and *departamento* being potentially impacted from an accumulation of 300 kg/m^2. Figure 2b and Online Resource 2 show the ratio of buildings of type 1 on the total amount of buildings in each administrative unit.

2.2.5 Territorial vulnerability

The domain of territorial vulnerability embraces the study of the vulnerability of critical infrastructures as well as their interconnectivity within a given system (Hellström 2007). Critical infrastructures are defined (1) by Moteff et al. (2003) as ”those structures whose prolonged disruption could cause significant military and economic dislocation“ and (2) by the German authority Bundesamt für Sicherheit in der Informationstechnik (BSI 2004) as ”organizations or facilities of key importance to public interest whose failure or impairment could result in detrimental supply shortages, substantial disturbance to public order or similar dramatic impact“ (Hellström 2007). The aim of such an assessment is not only the evaluation of the vulnerability of all critical facilities, but also the evaluation of the vulnerability that arises from the fact they are interconnected. Since tephra fallout has the power of disrupting the functioning of interconnected systems (e.g. road network, electricity lines), this study provides a first attempt to evaluate dynamically possible consequences of such a threat on a large-scale system.

A complete global analysis of such systems has never been achieved and would require an enormous amount of precise georeferenced data. In our study, we considered (1) the road network, (2) the geographical position of airports, (3) the number of military bases and hospitals averaged for each administrative unit and (4) digital elevation models (DEM). Blong (1984) reports the disruptions of the road network following the Mount St Helens tephra fall of May 18, 1980, including poor visibility, slippery roads, altered traffic volumes and speed reduction. Additionally, severe damage to vehicles was reported due to the strong abrasive power of tephra. As a result, a maximum value of 100 kg/m^2 was defined in this study as enough to paralyse the road network. Airports and air traffic, as previously mentioned, are highly sensitive to tephra. Considering that thickness in the order of a few millimetres can already be problematic, this study considers that all airports located within the 1 kg/m^2 area ($\sim$1 mm, using a density of 1,000 kg/m^3) as non-operational. Finally, we assumed that critical facilities such as military bases and hospitals were designed to resist the highest values of tephra load before collapsing (i.e. 300 kg/m^2).

Our territorial vulnerability assessment was based on two indicators: i) the number of military bases and hospitals per administrative unit ii) and the cost distance to the closest airport via the road network, including a topography effect. Cost-distance mapping is a useful GIS tool which aims at mapping the ease of access between two points, where a low cost represents an easier access. Here, we have created a raster from the road network, assigning a higher travel cost to small roads than to primary roads and highways. In order to constrain the model to calculate access routes via the road network, a very high travel cost was assigned to any land other land that is not a road. The process consists in calculating the cost distance from any point of our calculation grid to reach the closest airport, adding topographical effects obtained from a digital elevation model. Results were then averaged for each administrative level and combined with the number of military bases and hospitals. The final value gives an approximation of the travel cost, where a high value means difficulty to travel.

The resulting map for territorial vulnerability can be found in Online Resource 1. Administrative units comprising important urban centres (*Quito, Santo Domingo de los Colorados, Ambato*) show the lowest levels of territorial vulnerability. Such a result requires some considerations. First, the OpenStreetMap dataset has major discrepancies in the accuracy of data in urban versus rural areas. As an example, some administrative units in *La Amazonìa* region are without roads, making a significant comparison of the resulting vulnerability score impossible amongst administrative units within the same study area. Second, the method adopted for the present systems mainly aims at assessing the redundancy of roads and critical infrastructures. The territorial vulnerability is inherited from (1) the ubiquity of critical infrastructures and (2) the high population density depending on these main infrastructures. The number of people dependant on a critical infrastructure was not included in our calculation and could potentially increase vulnerability indices in major urban centres.

3 Risk assessment

The objective of risk assessment and risk mapping is to depict the spatial intensity variation of both hazard and vulnerability. Thematic risk maps are necessary tools for policy managers and administrators to develop the most suitable land use, planning for risk reduction and appropriate actions to adopt in case of an emergency phase (Lirer and Vitelli 1998; Torrieri 2002). According to the United Nations Disaster Relief Office, risk can be defined as "the expected number of lives lost, persons injured, property damaged and economic activity disrupted due to a particular natural phenomenon" (UNDRO 1991). The quantification of risk may be determined using the following relationship (UNESCO 1972; Fournier d'Albe 1979):

$$R = E \times V \times H \tag{1}$$

where R is the risk, E is the element at risk (a value describing the number of human lives, a capital value or a productive capacity), V is the vulnerability level as defined in Table 1, and H is the volcanic hazard, or the probability of any particular area being affected by a destructive volcanic manifestation within a given period of time. The establishment of such a relationship marked the change from early risk assessments, which usually considered the vulnerability aspect as solely a matter of structural resistance of infrastructures reduced to a simple exposure value, generally adopting a Boolean approach of 0 (no exposed element) or 1 (exposed elements) (Barberi et al. 1990).

Due to the wide range of possible impacts of tephra on all different facets of vulnerability (Table 2), Eq. 1 is not suitable for all aspects of vulnerability considered here. In this study, a more general relationship adapted for case-by-case risk analysis was used:

$$R = f(E, V, H) \tag{2}$$

The following sections accurately describe how hazard and vulnerability assessments were combined for each theme to compile thematic qualitative risk maps. Vulnerability, hazard and risk indices for all administrative units are summarized in Online Resources 3, 4 and 5, respectively.

3.1 Social risk

Impacts of tephra fallout on human populations range from acute and chronic health effects (Blong 1984; Sigurdsson et al. 2000; Horwell and Baxter 2006; Hincks et al. 2006) to pollution of water supply (Blong 1984; Stewart et al. 2006) and disruption of the economy (Blong 1984). Precise studies after major eruptions have shown the complex and nonlinear response of these aspects to tephra fallout (Johnston et al. 2000). Therefore, uncertain and wide ranges of individual exposures, natural variation in individual response, change in eruptive behaviour with time and meteorological conditions at the time of the eruption increase the difficulty of producing risk assessment for social aspects (Hincks et al. 2006). As an example, our social vulnerability maps are very simplified and only consider the aspects of (1) total population, (2) education level and (3) age classes, on which the effects

Table 2 Summary of hazardous thresholds of tephra used for each vulnerability theme

Vulnerability theme	Hazard thresholds (kg/m^2)	Elements at risk
Social	–	Population
Economic	5–150	Crops
Environmental	5–1500	Intact forests, natural areas
Physical	100–300	Buildings, roofs
Territorial	0–100	Roads, critical facilities

The range of hazardous accumulation describes the range in which hazard index linearly increases from 0 to 1 of tephra fallout are mainly unclear and indirect. As a result, we did not compile any social risk maps.

3.2 Economic risk

As described in Sect. 2.2.2, the qualitative economic analysis presented here is based solely on the agricultural production, which is the dominant source of income for the majority of rural areas around Cotopaxi volcano. Literature abounds with reports on both positive and negative effects of tephra deposition on crops (Inbar et al. 1995; Wisner et al. 2004; Martin et al. 2009), with the most comprehensive database of damage on different types of crops found in Blong (1984) presenting a survey of the impacted vegetation following the 1943–1952 eruption of Paricutin volcano (Mexico).

Considering a density of the deposit of 1,000 kg/m^3 and following the approach of Blong (1984) described in Sect. 2.2.2, we have defined here the hazardous range of tephra fallout for the risk assessment on crop as ranging from 5 to 150 kg/m^2. For each hazard scenario, the output hazard raster was reclassified in order to assign a hazard index linearly increasing from 0 to 1 between tephra accumulations of 5–150 kg/m^2, with a constant value of 1 above 150 kg/m^2. The hazard index was then averaged on the area of each individual administrative unit, including two standard deviations in the final hazard index to take into account the variability related to the irregular shapes of administrative units. The risk index was calculated as the multiplication of this hazard index by the economic vulnerability index defined in Sect. 2.2.2, resulting in values comprised between 0 and 1. Five risk classes were defined: *Very low* (0–<0.2), *Low* (0.2–<0.4), *Medium* (0.4–<0.6), *High* (0.6–<0.8), *Very high* ($\geq$0.8). The entire process was applied to all eruption scenarios.

Online Resource 2 contains all the final economic risk analysis for all scenarios considered in the hazard assessment, and Fig. 3a shows the economic risk considering an eruptive scenario of the type ERS of VEI 4. As expected, the risk decreases with distance from the volcano and with decreasing size of eruptive events. The areas of *Archidona, Mulalo, Machachi, San Juan de Pastocalle, Tanicuchi* and *Aloasi* are the most affected parishes in all scenarios.

3.3 Environmental risk

The analysis of the environmental risk was carried out based on the vulnerability approach described in Sect. 2.2.3. The hazardous thresholds used range from 5 kg/m^2 (minor damages to vegetation) up to 1,500 kg/m^2 (near total kill zone) in agreement with Blong (1984). The resulting risk indices were calculated as the product of hazard and vulnerability, for each eruption scenario. Similarly to the economic risk, resulting risk indices are comprised between 0 and 1, and the same risk classes were applied to the environmental risk.

3.4 Physical risk

The risk for infrastructures was based on the classification described in the Sect. 2.2.4, and with hazardous tephra thresholds ranging from 100 to 300 kg/m^2. Using a simple logic script, we have defined that:

- Buildings of type 1 collapse with a tephra accumulation of 100 kg/m^2,
- Buildings of type 2 collapse with a tephra accumulation of 200 kg/m^2,
- Buildings of type 3 collapse with a tephra accumulation of 300 kg/m^2,

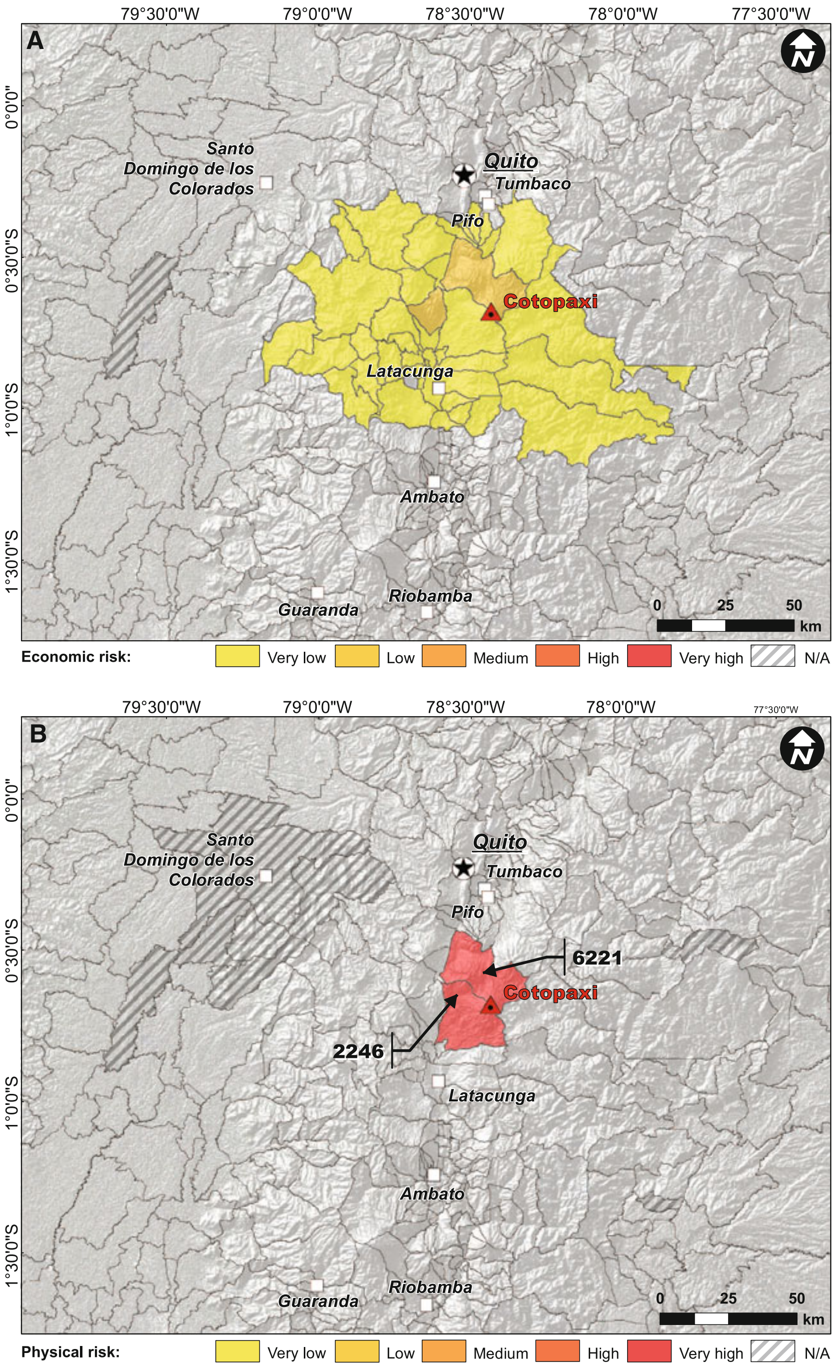

Fig. 3 Thematic risk maps per *parroquia* based on an eruptive scenario of type ERS of VEI 4 showing **a** economic risk with qualitative subdivisions of the risk level and **b** physical risk showing the number of buildings expected to collapse in each administrative unit. *N/A* refers to gaps in the census survey. Risk maps for all themes and all eruptive scenarios can be found in Online Resource 2

which allows for a quantitative estimation of the number of buildings likely to be affected by a given eruptive scenario within each administrative unit. The risk maps show both qualitative and quantitative classifications. First, the colour scheme based on risk classes is defined as the proportion of collapsed buildings for a given eruption scenario, classified as *Very low* (0–<20 %), *Low* (20–<40 %), *Medium* (40–<60 %), *High* (60–<80 %), *Very high* ($\geq$ 80 %). Second, the number of building collapsing for each eruption scenario is also indicated for each administrative unit.

The resulting risk maps show a higher risk in administrative units located in the proximal and downwind areas and decreases away from the vent (Fig. 3b), which do not contain high densities of population (Fig. 1). Figure 3b is the resulting physical risk map considering an ERS of VEI 4 where the two closest parishes (*Mulalo* and *Machachi*) have values of building collapse of 2246 and 6221, respectively, corresponding to a loss of 100 % of the buildings in both cases. Physical risk maps for all eruptive scenarios are shown in the Online Resource 2.

3.5 Territorial risk

The risk component of the assessment of the inter-dependency of systems was assessed using the only geographical features available, namely roads and airports. Hospital and military bases considered in the vulnerability assessment were inferred from the 2001 *Censo de poblacion y vivienda from the Instituto Nacional de Estadísticas y Cencos de Ecuador* (INEC) and therefore averaged to administrative units.

A cost-distance mapping to the closest airport via the road network was achieved by assigning weights to the different road classes. Our territorial risk assessment included a second weighting of the road network depending on the tephra accumulation on the ground, and performing a second cost-distance mapping excluding airports comprised within the 1 kg/m^2 area (see Sect. 2.2.5). In the absence of reports of relationship between ground-deposited tephra and blockage of the road transportation, sensible tephra thresholds for the road network were defined from ranging between 0 and 100 kg/m^2, with blockage of the roads occurring at this highest level. Relative weighting of the road network was performed by increasing the weight of roads depending on the amount of tephra, reaching an equal weight as "free land" when impacted with 100 kg/m^2 or more of tephra. An arbitrary risk classification was defined using Jenks (1967) methods on the final cost-distance values related to a moderate eruption (i.e. ERS for VEI 4), which was then applied to all eruption scenarios.

Although high territorial risk values occur biased towards administrative units that do not have complete information of road network, these maps can be viewed as a first attempt to describe the disruption within an interconnected system. Territorial risk maps can be found in Online Resource 2.

4 Discussion

We have developed a method for a fast and remote qualitative assessment of the vulnerability and the risk related to tephra fallout. The methodology was applied to Cotopaxi volcano, for which a thorough hazard assessment is described in Biass and Bonadonna (this volume). In this paper, we propose the use of isomass maps for a given probability (e.g. Fig. 1) when combining probabilistic hazard modelling and vulnerability assessments. In fact, isomass maps for given probability levels (e.g. 50 %) make the evaluation of the exposure clearer to decision-makers and the identification of the potential losses faster for governments. The acceptable levels of risk required to compile isomass maps are of complex identification (Marzocchi and Woo 2009; Villagrán de León 2006).

4.1 New strategy for risk assessment

The methodology used here to assess the risk is based on global and free georeferenced datasets. The final product is a thematic risk assessment, where the definition of the different themes is strongly related to the hazard considered and the availability of georeferenced data. Here, and in agreement with the work of UN/ISDR (2004), five vulnerability themes relevant to tephra fallout were identified, ranging from strictly physical and structural vulnerability to socio-economic and territorial aspects. The hazard related to tephra fallout is characterized as a long-lasting low-intensity phenomenon, as it does not directly kill but it is able to affect human activities for days, weeks or months, and often requires heavy cleaning operations (Blong 1984; Johnston et al. 2000; Wilson et al. 2011c). As a result, a study of the physical domain is important as whole buildings can collapse under tephra blanketing; an evaluation of the territorial aspect helps to understand the complex large-scale disruptions of different networks; socio-economic aspects help to assess government costs of such a large-scale hazard. On the contrary, hazards associated with phenomena such as lahars or lava flows are mainly likely to disrupt the physical domain (i.e. burrial and burning processes) and would require a smaller number of themes to be relevant. Specifically to Cotopaxi volcano, this approach differs from previous risk assessments (D'Ercole 1996; D'Ercole and Demoraes 2003), which considered the risk based on social vulnerability only, and proposes similar approaches towards all volcanic hazards.

Our method strongly relies on the national Ecuadorian census (INEC 2001), which provides socio-economic indicators and a building census averaged at the fourth level of administrative unit (Admin 4, *Parroquia*). The end product of this method is a vulnerability/risk ranking per *parroquia* displayed on a map, similarly to the work of Aceves-Quesada et al. (2007). Considering the limitations of the use of maps as a communication tool listed by Handmer and Milne (1981), Newhall (2000) and Haynes et al (2007), a few observations can be made. First, most people find difficult to locate themselves on a map, to interpret topography or to estimate the extent of a contoured zone (Haynes et al. 2007). Contour-based maps are thus often an ineffective method to communicate hazard and risk information (Handmer and Milne. 1981), and some authors adopt risk ranking without any map display (Magill and Blong 2005a, b). Ranking per administrative units allows for an easy localization process by administrative unit, as well as for a comprehensive geographical comparison of the vulnerability and risk levels over a region of interest. Although a contour is still inherent, it does not involve an equally sharp boundary and provides the reader with an easier concept of a gradual variation of the risk levels. Second, Newhall (2000) argues that "*although maps are everyday tool for volcanologists, they are too abstract and difficult for many users of volcano warning*". As previously mentioned, the aim of the maps produced by our method is to give an overview of the vulnerability and risk levels over a large scale, and these maps do not aim at assisting emergency management at a local scale. For this purpose, this method might provide a more efficient communication tool than contour-based (i.e. Lirer and Vitelli 1998; i.e. Thierry et al. 2008) or pixel-based maps (i.e. Alberico et al. 2008; i.e. Lirer et al. 2010).

This approach aims at producing fast remote vulnerability and risk assessments, which do not require a strong knowledge of the area and do not rely on precise (and thus often expensive) georeferenced datasets. As a result, both vulnerability and risk assessments consider an equal importance of indicators within a given theme, and an equal importance of all themes. This simplified approach is clearly not entirely valid in practice, as socio-economic and cultural contexts vary amongst countries. As an example, D'Ercole and Demoraes (2003) produced a large-scale multi-hazard risk assessment in Ecuador using the knowledge of NGOs to weight the relevant indicators. In this regard, the use of Multi-Criteria Evaluation (MCE) techniques within GIS platforms to assist decision-making has received an increasing attention during the past decade (Joerin et al. 2001; Torrieri 2002; Malczewski, 2006; Aceves-Quesada et al. 2007). MCE allows for a number of factors to be integrated, for decision rules and hierarchies to be applied (Aceves-Quesada et al. 2007) and is integrated in most of current GIS platforms. As a result, our method provides vulnerability and risk assessments in which all indicators and themes have a weight of 1. MCE techniques could help to redefine these weights based on a wider knowledge of social and economic aspects of a region.

Assessing the risk of tephra fallout requires the identification of critical thresholds of tephra accumulation for each theme. The definition of hazardous thresholds usually relies either on thorough field investigations after an eruption (Blong 1984; Inbar et al. 1995; Spence et al. 1996; Johnston et al. 2000; Blong 2003; Martin et al. 2009; Wilson et al. 2011a, b, c) or on a combination of theoretical and laboratory experiments (Spence et al. 2005; Stewart et al. 2006), and they are often geographically constrained due to several factors (i.e. variability of the type/composition of volcanic products, climate, quality of exposed elements). Here, we have defined simplified hazardous thresholds based on a literature study for all themes except for social aspects, where the relationship between exposed populations and tephra fallouts require further investigations. In the case of economic and environmental themes, we have assumed a linear increase in the impact levels between general impact boundaries. A refinement of these boundary values as well as the impact response considering the vegetation species present in the area is necessary. In the case of the economic theme, the identification of the main types of crops as well as the definition of their monetary value would result in an efficient impact assessment. The physical assessment, helped by a local knowledge of the area (Hugo Yepes, personal communication), results in a quantitative assessment of the number of buildings likely to collapse, which could be expressed as cost if a monetary value was defined for each building class identified in Sect. 2.2.4. The territorial assessment was carried out to evaluate the interconnectivity of critical infrastructures and consisted in the investigation of the theoretical accessibility of airports based on the road network. While the thresholds for airports closure are commonly agreed to be around a few millimetres (Bonadonna 2006; Guffanti et al. 2009), a large variability of tephra accumulation is reported to affect and paralyse the road network, depending on the distance from the vent (e.g. deposit grain size) and on the climate (e.g. dry/rainy conditions) (Blong 1984; Wilson et al. 2011c). Here, a progressive linear blockage of the road network was assumed to occur between 0 and 100 kg/m^2, as the elaboration of more precise response curves would require to incorporate a large number of independent factors. As a result, the definition of hazardous thresholds of tephra fallouts on exposed elements is often the main difficulty to compilation of risk assessments. Recent studies show important advances in the topic of agriculture (Wilson et al. 2011a, b), buildings (Spence et al. 2005; Marti et al. 2008) and critical infrastructures (Stewart et al. 2006; Bebbington et al. 2008; Wilson et al. 2011c), allowing for new methods for risk assessment to be developed.

Finally, although the risk assessment carried out here is restricted to some specific aspects, the methodology can be used as a basis to develop a more complete approach to volcanic risk assessment. In particular, our social and economic vulnerability assessments use global indicators that fail to capture complex socio-economic patterns. The social vulnerability relies on three indicators (age, education level, proportion of children/seniors/invalids), whereas more comprehensive definitions relate social vulnerability to complex issues such as levels of well-being of individuals, gender, health, literacy, education, the existence of peace and security, access to human rights, social equity, traditional values, beliefs and organizational systems (Villagrán de León 2006). Additionally, many indigenous communities live in and around the province of Cotopaxi (INEC 2001), which are known to add complexity to patterns of social vulnerability and resilience, and require the use of specific indicators (Ellemor 2005; Gaillard 2007; Cashman and Cronin 2008). Similarly, economic vulnerability, defined here as depending only on agriculture, comprises factors such as levels of individual, community and national economic reserves, levels of debts, degrees of access to credits, loans and insurance and economic diversity (Villagrán de León 2006). As a result, detailed datasets are required to define more precise indicators, which would result in a more accurate risk assessment. Also, this methodology relies on the technique of Jenks (1967) to define vulnerability classes, which considers the observed population as uniform. In the case of the presence of different communities with distinct socio-economic contexts, this assumption can lead to a misinterpretation of the vulnerability of minorities.

4.2 Caveats

- Our method can mainly be used to compare vulnerability levels of some themes amongst administrative units. Due to the dependence on the nature of the datasets used to evaluate the vulnerability, this method cannot be used to compare the vulnerability of two different geographical and cultural regions.
- Our method depends on the availability and completeness of free and global data. As an example, the OpenStreetMap dataset is a very promising source of georeferenced data, but currently lacks of homogeneity in the precision between different parts of the world, and between urban and rural areas.
- Our method is based on statistical strategies to divide the whole datasets of resulting vulnerability indices into a global vulnerability value, which implies that the definition of the classes is related to the nature and the statistical distribution of the data (Jenks 1967). Vulnerability classes presented here are strongly related to the datasets used in this study and do not rely on previously defined thresholds.
- Major assumptions are made in the definition of our vulnerability indicators (e.g. economic aspects described solely with the proportion of agricultural lands).
- No aspect of coping capacity or resilience was included in our social vulnerability assessment.
- Sharp boundaries between vulnerability classes fail to describe the gradual transition between different geographical features.

4.3 Risk assessment of Cotopaxi volcano

Our field and literature analysis has shown the capacity of Cotopaxi volcano to produce large explosive eruptions, always followed by tephra fallout and lahars (Barberi et al. 1995; Hall and Mothes 2008; Biass and Bonadonna 2011). Combining our hazard assessment (Biass and Bonadonna, this volume) with the vulnerability analysis presented in this paper, we conclude that:

Between $\sim$18,000 (ERS VEI 3) and $\sim$820,000 (ERS VEI 5), people could be affected by tephra fallout of $\sim$ 1 kg/m^2, with consequences on public health (respiratory problems, eye irritation) and rapid abrasion of household facilities (cars, air conditioning systems). This amount of tephra covers areas between $\sim$ 2,000 and $\sim$80,000 km^2 (ERS for VEI's 3 and 5 respectively; Biass and Bonadonna, this volume), with significant economic consequences related to the closure of the Mariscal Sucre Airport of Quito.

Areas between $\sim$ 300 and $\sim$ 18,000 km^2 (ERS for VEIs 3 and 5, respectively) could be affected by an accumulation of tephra of 10 kg/m^2 (about 1 cm). As shown in Fig. 1, the area most likely to be impacted is located west of the volcano, along the direction of prevailing winds, with consequences on (1) the important Panamerican Highway, which connects the Southern towns and cities of the Interandean valley to Quito and (2) the rural areas located around the town of Latacunga. The tephra threshold of 10 kg/m^2 can therefore seen as critical in this area, bearing impacts on both accessibility and communication networks as well as on the local economy (i.e. damage to crops).

Finally, the area threatened by collapse of the weakest roofs varies from $\sim$30 to $\sim$2,400 km^2 (ERS for VEI 3 and 5, respectively, threshold of 100 kg/m^2), west of the volcano.

As a result, the combination of a highly explosive behaviour of Cotopaxi volcano coupled with the close presence of both multiple human settlements and critical facilities could result in acute situations in the context of a volcanic crisis, even with the scenario with the lowest intensity considered in this study (ERS for VEI 3). High risk arises from (1) the proximity of the Mariscal Sucre airport of Quito, acting as a main communication hub, (2) the importance of agriculture on the local economy and (3) the structural situation of the Panamerican Highway coupled with a lack of redundancy of main roads. Furthermore, the risk situation in the Interandean valley is even more complex, as the volcanic threat does not come solely from Cotopaxi volcano, but from a whole range of active and potentially dangerous volcanoes (Guagua Pichincha, Reventador, Tunguraghua). The development of a comprehensive land use planning, an eduction programme dedicated to raise the awareness of local communities to volcanic threat as well as the elaboration of proper evacuation schemes incorporating eruptive scenarios might help to reduce the level of risk around Cotopaxi volcano.

Placing back this methodology in the context of an ongoing effort to assess volcanic risk, we have developed a method specifically designed for the risk associated with tephra fallout. Looking at the available literature on risk assessment of volcanic areas, important points can be highlighted:

- Due to the precision of the available georeferenced datasets and the scale of the study area, our vulnerability and risk assessments have been averaged to the smallest level of administrative unit available. This approach, similar to the method of Aceves-Quesada et al. (2007) for vulnerability assessments, differs from the approach of risk zonation used, for example, by Lirer and Vitelli (1998) and Thierry et al. (2008). This is due to the nature of the population census, which provides indicators averaged per administrative unit. The resulting maps present the geographical distribution of vulnerability and risk levels of the administrative units across the study area, which allows for a rapid comparison amongst the three different regions of the country, in contrast with detailed zonations able to describe the risk at smaller scales.

- Rather than assessing the global vulnerability or risk to one or several threats and provide global maps (Aceves-Quesada et al. 2007; Thierry et al. 2008), this method aims to draw thematic vulnerability and risk maps in order to underline the characteristics of each administrative unit and to enhance the geographical comparison previously discussed.
- The final aim of such a method is to provide a robust quantitative estimate of the risk to decision-makers, which requires the definition of a unit of risk. Currently, the most commonly used unit is monetary value, which requires precise data and a proper knowledge of the study area. Our methodology cannot yet provide a quantitative risk assessment based on monetary values, but it provides a fast and comprehensive strategy that can easily be applied remotely at regional levels and can be implemented once more detailed information is made available.

5 Conclusion

This study is a first step towards a fast comprehensive risk assessment for tephra fallout of areas located in the vicinity of active volcanoes. The methodology presented here is an alternative to the use of expensive and scarce high-resolution georeferenced dataset and is based on open-source and free global data. It is relatively fast and flexible and could be used even remotely as a fast tool for short-, mid- and long-term analysis in the context of contingency planning, land use planning and decision-making.

Main outcomes of this method are:

- A qualitative thematic vulnerability assessment (i.e. social, economic, environmental, physical and territorial), with indicators for each theme designed to specifically describe the vulnerability towards tephra-related hazards.
- A costless assessment based on free datasets such as OpenStreetMap (roads, place names, airports), GlobCover (land cover), WDPA (protected areas), Greenpeace (intact forest landscape) and SRTM (digital elevation model).
- A new way of using a probabilistic hazard assessment of tephra dispersion in combination with a vulnerability assessment, based on the compilation of isomass maps for a given probability threshold.
- A thematic risk assessment, including a quantitative estimate of building losses caused by extreme tephra load, and a first attempt to dynamically describe the impact of tephra fallout on the interconnectivity of communication network using GIS tools based on critical values of tephra for airport closure and disruption of the road network. It also compiles estimates of the economic and environmental risk levels. Due to the complex impact range of tephra fallout on social aspects of vulnerability, the compilation of risk maps was not yet possible.

Regarding Cotopaxi volcano:

- The risk being defined as a function of hazard and vulnerability, the proximity of an active volcano to a high population density confined in a valley makes the surrounding populations exposed to high levels of risk.
- The importance of agriculture as a source of income in this area would lead to socio-economical impacts in case of tephra fall, and the occurrence of an eruption of medium intensity similar to the one used in this paper would have a 50 % probability of affecting agricultural activities in an area of about 6,000 km^2.

- The combined exposure and structural confinement of the Panamerican Highway on the bottom of a valley would induce strong communication problems in the case of a blockage of the road network due to tephra fallout.
- In most of our eruption scenarios, Quito is exposed to light tephra deposition (e.g. 50 % probability of an accumulation of tephra $\geq$ 1 kg/m^2 for an eruption of VEI 4), exposing the international airport to a possible closure. Similarly, the airport of Latacunga is likely to close even during small eruptions, and the airport of Ambato suffers similar probabilities of closure as the airport of Quito. Even though these airports are of smaller importance compared to the international hub of Quito, their closure could be problematic if rapid transportation during a volcanic crisis is required.

At a parish level:

- The economic risk is the highest in the eastern part of the Cotopaxi province (parishes of Guaitacama, Joseguando Bajo, Poalo, San Juan de Pastocalle, Tanicuchi, Toacaso, Saquisili, Chanchagua and Chantilin) and the southern part of the Pinchincha province (Machachi, Aloasi, El Chaupi).
- The environmental risk is high in the province of Cotopaxi due to the presence of natural reserves, and in the province of Napo due to the Amazonian forest.
- The physical risk is high for parishes close to the volcano, with the two most affected parishes of Mulalo and Machachi having a 50 % probability of having a collapse of 100 % of the buildings (i.e. ~2,200 and ~6,200 buildings, respectively) in the case of an eruption of VEI 4.

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